About Impedance-Matching with Transmission Lines

Use transmission lines to convert impedances.

H. Ward Silver, NØAX

In the previous article,[1] "About Impedance-Matching Circuits," we discussed what impedance is, and learned that what we call "impedance matching" is really "impedance converting." We reviewed several circuits and components that perform impedance conversion.

This article covers other methods of converting impedance using the properties of transmission lines. Special lengths, combinations, and connections of feed lines can be used. At antenna feed points, the same ideas can be used to create structures that convert impedances, too.

Feed Lines and Impedance

We start with a feed-line *characteristic impedance*, abbreviated Z_0. This tells us what voltage and current are created by power flowing in a feed line. Just like in a circuit, Z_0 tells us the ratio of voltage and current, but this time, in the line.

To experience a mechanical analogue of characteristic impedance, get a small-diameter coffee stirrer and a large-diameter drinking straw. Blow a short, sharp puff of air through each. Even though you blow equally hard into each (voltage) you get only a little air through the small tube (current), but a lot of air gets through the large one. The small tube has a higher characteristic impedance to pressure waves.

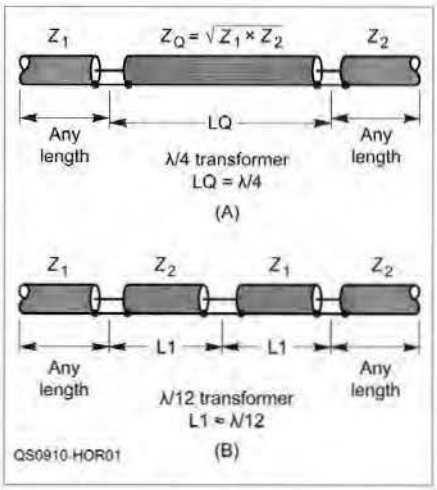

Figure 1 — The quarter-wave and ½-wave synchronous transformers. The series of reflections created by the impedance mismatches at each end of the matching sections creates the impedance conversion.

Back to RF — if power flowing in a feed line encounters some impedance other than Z_0, such as a different type of feed line, the voltage and current change abruptly at the junction. To create this change, the initial wave splits into two; one in the new feed line and one reflected back toward the source in the original feed line. Just like water waves reflecting from a wall or rock, a pattern of interference is created between the incoming *forward* wave and the *reflected* wave. Even though both waves are moving, the voltage and current interference patterns are stationary, called a *standing wave*. The *standing wave ratio* (*SWR*) is the ratio of the maximum to minimum voltage or current in the pattern. See the sidebar, "Explaining SWR in Black and White."

> *"Just like in a circuit, Z_0 tells us the ratio of voltage and current, but this time in the line."*

Hams are counseled to minimize SWR, because standing waves created by the reflected power have higher peak voltages — increasing *dielectric loss* — and higher peak currents — increasing *resistive loss*. Feed line loss in general is dissipation of the RF signal as heat by any means; dielectric loss occurs in the insulation between the center conductor and shield, caused by the ac voltage between the conductors. Resistive loss is caused by the resistance of the center conductor and shield to ac current, and is proportional to the square of the current. As frequency increases, so do both dielectric and resistive losses.

In addition, after the reflected power makes its way back to the source, such as a transmitter, it can be reflected again, heading back to the load or the antenna. Each unwanted extra trip through the feed line results in loss, until all of the power is either transferred to the load or dissipated as heat. To avoid loss, we try to match the line and load impedances, minimizing reflections and SWR.

Inefficient power transfer into a receiving system due to a large impedance mismatch can also reduce receive sensitivity or decrease signal-to-noise ratio. As mentioned in the previous article, "About Impedance-Matching Circuits," the reflected waves at a transmitter combine with the transmitter's output, creating an impedance that might not be what the transmitter was designed to drive.

There are ways to use the feed lines themselves to alter impedances so they match, or at least minimize the effects of the mismatch.

Synchronous Transformers

The most common uses of transmission lines in impedance matching are the *synchronous transformers*,[2] special lengths of feed line connected in series between an impedance to be matched at one end of the line (Z_{LOAD}) and a desired impedance at the other end (Z_{IN}). "Synchronous" means the reflections generated at the connections of the feed lines synchronize or add together to create the desired impedance at the input to the matching section. Two types are shown in Figure 1.

The most common example is the *quarter-wave* or *Q-section*, which uses a quarter-wavelength of feed line with $Z_0 = \sqrt{Z_{LOAD} Z_{IN}}$. A Q-section is often used to convert the approximately 100 Ω impedance of a full-wave loop to 50 Ω. In this case, the transformer section must have a $Z_0 = \sqrt{100 \times 50} = 70.7\ \Omega$. RG-59, RG-11, or 75 Ω hardline are popular choices. One set of reflections is created at the connection of the Q-section to the antenna's feed point and the other set at the connection to the 50 Ω feed line. The reflections all add together such that the antenna feed point is connected where the impedance is 100 Ω and the main 50 Ω feed line is connected at a 50 Ω impedance point. Anti-reflection coatings on lenses use the same principle of quarter-wave coatings to cancel reflections that cause glare.

The ½-wave section in Figure 1 helps amateurs make good use of all that 75 Ω hardline originally used for cable TV systems. For example, by placing a ½-wave transformer at the antenna and at the transceiver, a long run of inexpensive low-loss 75 Ω hardline can be used without raising SWR for antennas and transceivers designed for 50 Ω systems.

Synchronous transformers depend on the electrical length of the feed line being a particular fraction of a wavelength long. These are *single-band* transformers, unlike broadband ferrite transformers, for example. The greater the difference between the two impedances, the narrower the bandwidth of the match will be. Nevertheless, performance is generally acceptable over a single amateur band. The transformer section's Z_0 and the impedance of the load can vary up to 10% or so and still give acceptable results.

Explaining SWR in Black and White

For a terrific visual explanation of what SWR is, and how standing waves are created in a feed line, watch the video "Similarities in Wave Behavior" in the AT&T Archives on **youtube.com**. While it is rather old and in black and white, the information is timeless and Dr. Shive does a wonderful job of using his invention, the Shive Wave Machine, to clearly illustrate how waves work in feed lines and other media. It also makes a great club presentation.

Transmission Line Stubs

Impedance transformers made from feed line don't have to be in series with another feed line to work. They can also be connected in parallel. The most common transformer of this sort is called a *stub*.[3] (The name comes from the short length of feed line.) Like the in-series transformers, the stub creates a reflected wave that combines with the waves in the main feed line to change the impedance at that point. The electrical length of the stub, the termination at the far end of the stub, and the stub's Z_0 control the amplitude and phase of the reflected wave.

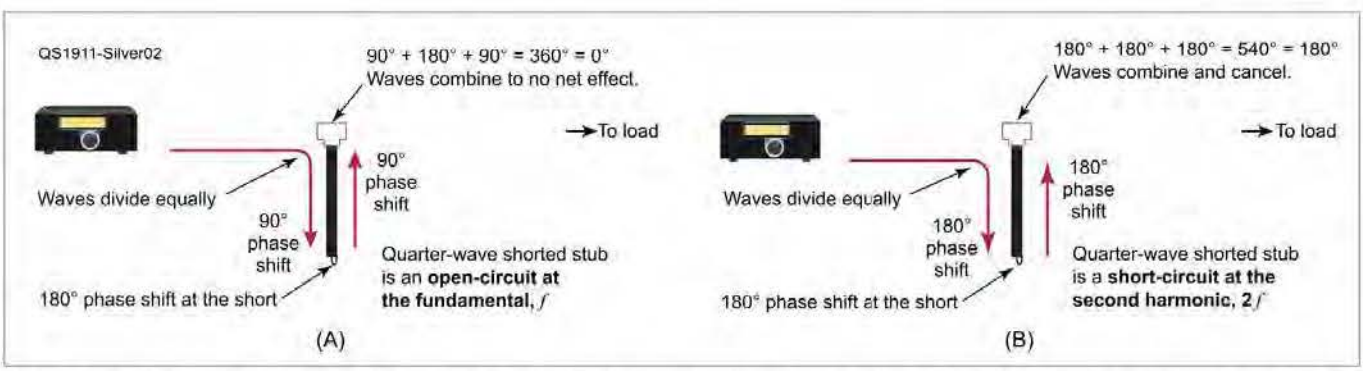
QS1911-Silver02
90° + 180° + 90° = 360° = 0°
Waves combine to no net effect.
To load
Waves divide equally
90° phase shift
90° phase shift
Quarter-wave shorted stub is an open-circuit at the fundamental, f
180° phase shift at the short
(A)
180° + 180° + 180° = 540° = 180°
Waves combine and cancel.
To load
Waves divide equally
180° phase shift
180° phase shift
Quarter-wave shorted stub is a short-circuit at the second harmonic, 2f
180° phase shift at the short
(B)

Figure 2 — Reflected waves in a quarter-wavelength shorted stub create an open circuit (A) at the feed-line junction, so there is no effect at the fundamental frequency. At twice the fundamental frequency (B), the stub is a half-wavelength long and creates a short circuit at the junction, acting as a harmonic filter.

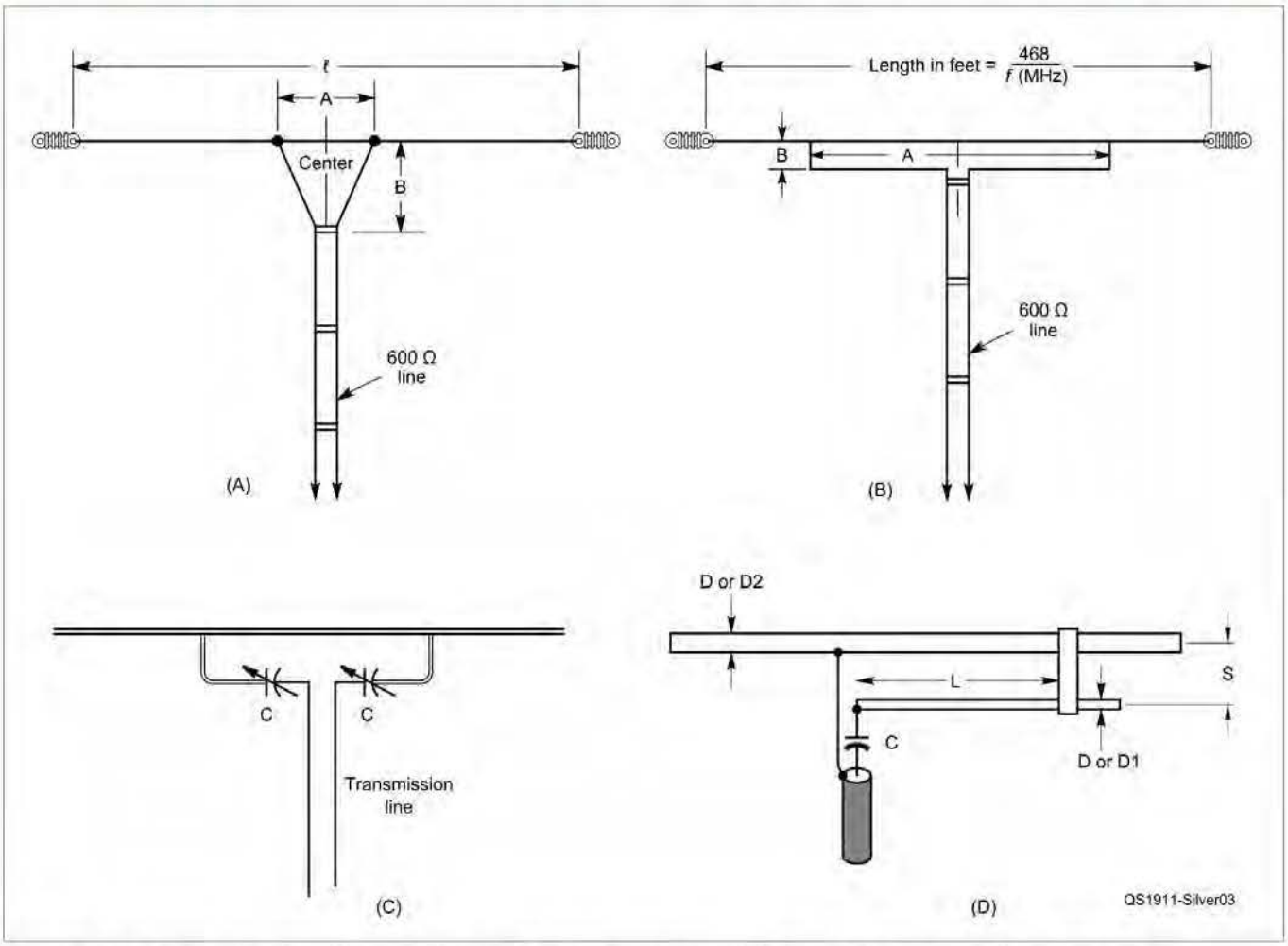

Figure 3 — The delta match (A) and **T** match (B) evolved (C) into the gamma match (D), which is popular for Yagis with a driven element attached directly to the boom. Dimensions A, B, D1, and D2 are adjustable for an approximate match, with C and L adjusted for the final match.

Returning to a mechanical analogy, using a stub to match an impedance is very similar to adding a weight on a tire's rim to balance a wheel. By itself, the wheel's imbalance sets up a vibration in the axle. The weight (or weights) added to the rim set up their own vibrations that are of just the right size and timing to cancel the vibrations from the wheel when they add together in the axle.

It is possible to use a single stub that's a quarter-wavelength long or less to match any impedance in a feed line to the desired impedance at a single frequency.[4] (The impedance to be matched can't be a pure reactance, a short, or an open circuit, and you also have to be able to connect the stub at just the right point in the feed line.) There are many different arrangements and methods of using stubs. You can use software like *TLW* by Richard Straw, N6BV, and *SimSmith* by Edward Harriman, AE6TY, to calculate exact electrical lengths, as well as experiment with different arrangements of stubs and series sections of feed line.[5,6]

Stubs can also act as band-pass or notch filters. For example, a shorted stub (terminated in a short circuit) a quarter-wavelength long at frequency, *f*, presents an open circuit (see Figure 2A) at the opposite end of the stub. As Figure 2B shows, the stub becomes a half-wavelength long at 2*f*, so it presents a short circuit at that frequency. You could use a shorted stub that's a quarter-wavelength long on 40 meters to short out or cancel a second harmonic on 20 meters. Stubs of this type are frequently used for reducing harmonics in multitransmitter stations, ARRL Field Day setups, etc. (A Field Day stub filter project is described in Note 3 and in *The ARRL Antenna Book*.[7]) Many stub applications can be found in George Cutsogeorge's, W2VJN, excellent *Managing Interstation Interference*.[8]

Antenna Feed-Point Matching

Rather than match antenna impedances somewhere in the feed line or back at the transmitter, it's preferable to provide a feed-point impedance of

50 Ω for direct connection of feed lines. Modern antenna design tools make that increasingly popular, but there are still many antennas that have feed-point impedances quite a bit different from 50 Ω.

You can put an antenna tuner right at the feed point, but it is less expensive in most cases to use one of the common matching structures instead. These mount directly on or at the antenna and require adjustment at the antenna. Typically, they are single-band solutions. The *gamma match* and the *beta* or *hairpin match* are the most common.

Gamma Match

The gamma match is an evolution of two earlier techniques; the *delta match* and the **T** *match*, as seen in Figure 3. Those techniques were used to match wire antenna impedances to open-wire line with Z_0 around 600 Ω. The delta match simply connected the feed line to points on the antenna with the right impedance, as determined by A and B. The **T** match created two short transmission line sections on each side of the antenna, transforming the impedance to that of the feed line.

The gamma match is actually one-half of a **T** match and is used with *unbalanced* antennas in which the driven element is connected directly to the boom and antenna support, which are at dc ground potential. This is a low-impedance point on the driven element and, aside from leading to imbalances in driven element current, it is convenient and sturdy.

Beta or Hairpin Match

The beta, or "hairpin," match is electrically an **L** network in which the driven element is deliberately made shorter than resonance to have a somewhat capacitive feed-point impedance. The hairpin inductor connected across the feed point transforms the driven element impedance to a pure resistance (see Figure 4D of Note 1). This requires the driven element to be insulated from the boom and, because the current balance in the driven element is important, an RF choke balun (or current balun) is required to isolate the feed line from the antenna.

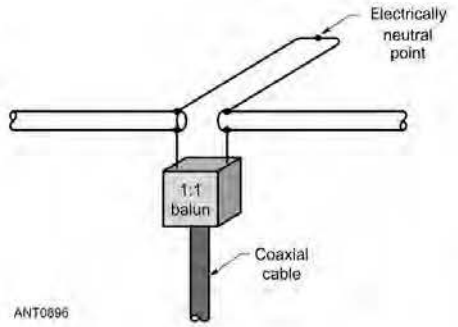

Figure 4 — The beta or hairpin match is actually an **L**-network with an inductor (the hairpin) connected directly across the feed point. The driven element's capacitive feed-point impedance acts as the remaining element of the **L**-network. The driven element must be insulated from the antenna boom, although the center point of the hairpin is electrically neutral and may be attached to the boom for support.

References and Tools

To really learn how to design and apply the techniques described in these articles, follow up with the notes and references given in each article. In addition, the ARRL Periodicals Archive (**www.arrl.org/arrl-periodicals-archive-search**) lists related articles from *QST*, *QEX*, *NCJ*, and *Ham Radio* magazines.

Must-have books for students of impedance matching include *Transmission Line Transformers* by Jerry Sevick, W2FMI (SK), and any edition of *Reflections* by M. Walter Maxwell, W2DU (SK). Online resources abound, including two of my favorites: RF Café (**www.rfcafe.com**) and Microwaves 101 (**www.microwaves101.com**), which feature numerous tutorials and calculator utilities.

Notes

[1]H. W. Silver, "About Impedance Matching — Circuits and Components," *QST*, Oct. 2019, pp. 43 – 46.

[2]"Hands-On Radio #81 — The Synchronous Transformer," all "Hands-On Radio" columns are available online at **www.arrl.org/hands-on-radio**.

[3]"Hands-On Radio #22 — Stubs," **www.arrl.org/hands-on-radio**.

[4]"Single-stub matching," **www.microwaves101.com/encyclopedias/smith-chart-basics**.

[5]*TLW* (*Transmission Lines for Windows*) is included with the *ARRL Antenna Book*, available from your ARRL dealer or the ARRL Bookstore. ARRL Item no. 0444. Telephone 860-594-0355, or toll-free in the US 888-277-5289; **www.arrl.org/shop**; **pubsales@arrl.org**.

[6]*SimSmith* is a free transmission line system design tool available online at **harriman.ddns.net/smith_charts.html**.

[7]Chapter on Transmission Line System Techniques, *ARRL Antenna Book*.

[8]G. Cutsogeorge, W2VJN, "Managing Interstation Interference," **www.inrad.net**.

Ward Silver, N0AX, has been licensed since 1972. He is lead editor of *The ARRL Handbook* and *The ARRL Antenna Book*, and is the author of all three editions of the *ARRL License Manual* and study guides. He released the well-received *Grounding and Bonding for the Radio Amateur* in 2017 and recently authored the third edition of *Ham Radio for Dummies*. An electrical engineer, Ward designed microprocessor-based products and medical devices for 20 years before beginning a second career as a teacher and writer. He is a cofounder of the World Radiosport Team Championships (WRTC), was inducted into the CQ Contest Hall of Fame in 2015, and is President of the Yasme Foundation. You can contact Ward at **n0ax@arrl.org**.

For updates to this article, see the *QST* Feedback page at www.arrl.org/feedback.